National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Challenges of Communications and Tracking for Solar System Small Body Exploration

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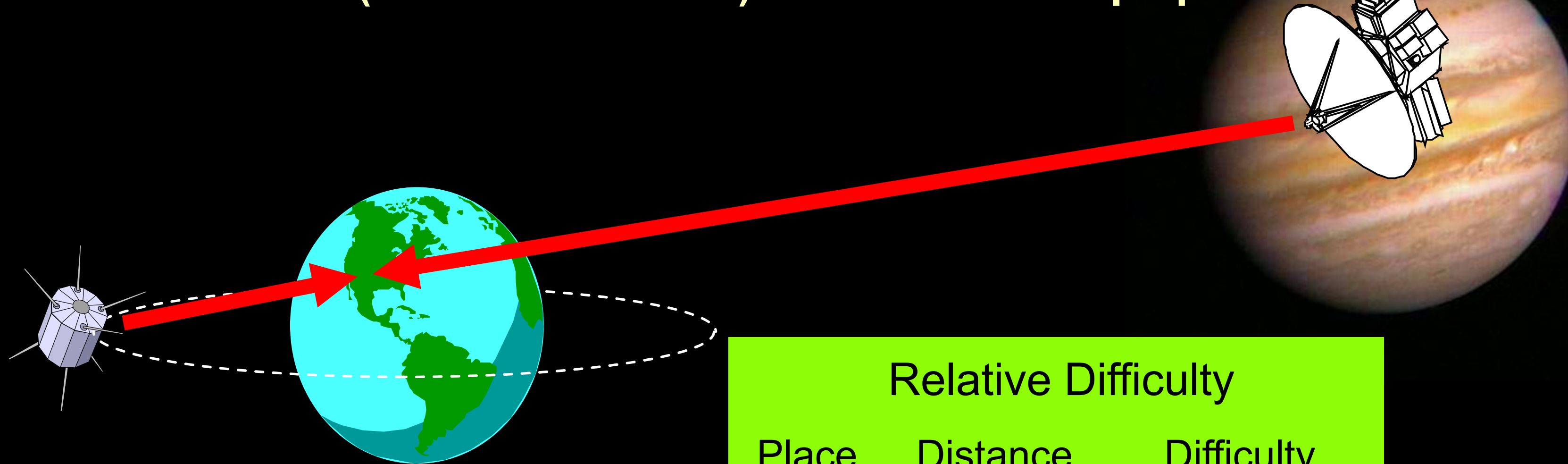
Why is Deep Space Communications So Difficult?

Communications performance decreases as the square of the distance.

Jupiter is nearly 1 *billion* km away, while a GEO Earth communications satellite is only about 40 *thousand* km away

- **It's about 87 dB (~1/2 billion times) harder from deep space!**

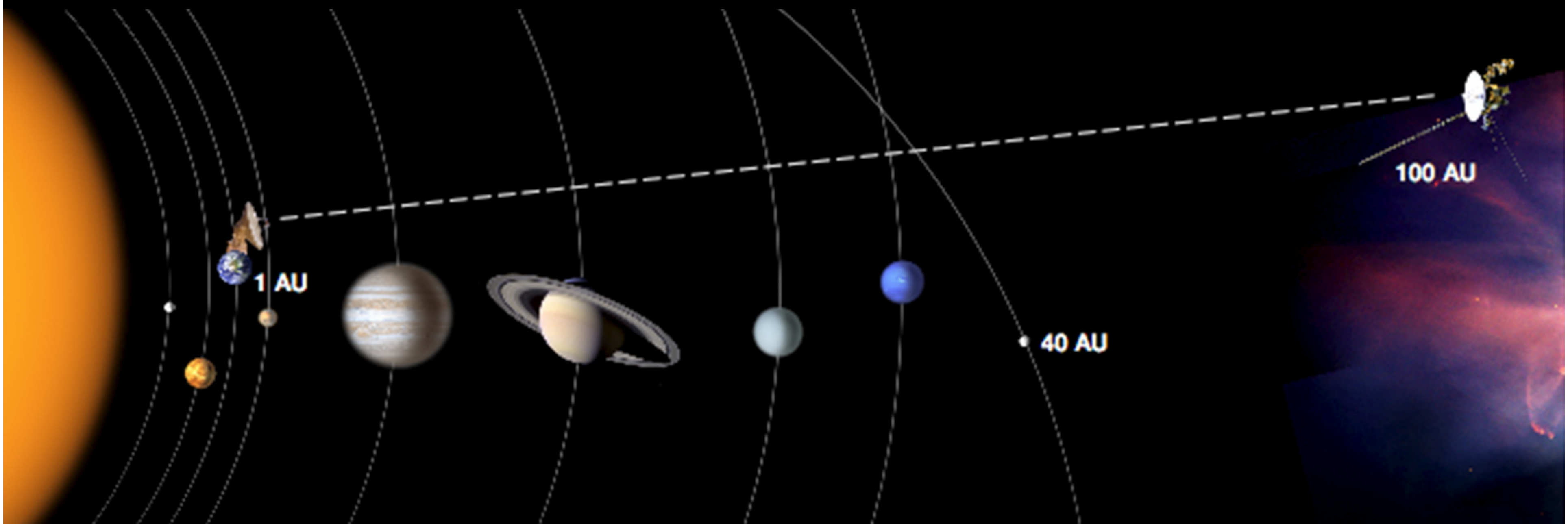


Relative Difficulty

Place	Distance	Difficulty
Geo	4×10^{4} km	Baseline
Moon	4×10^{5} km	100
Mars	3×10^{8} km	5.6×10^{7}
Jupiter	8×10^{8} km	4.0×10^{8}
Pluto	5×10^{9} km	1.6×10^{10}

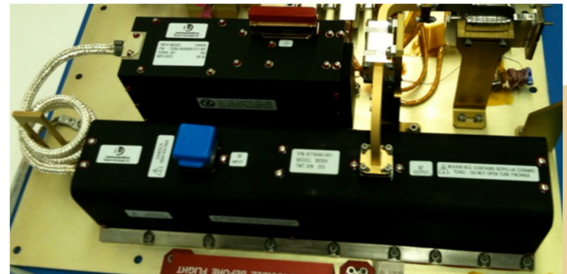
Said Another Way …

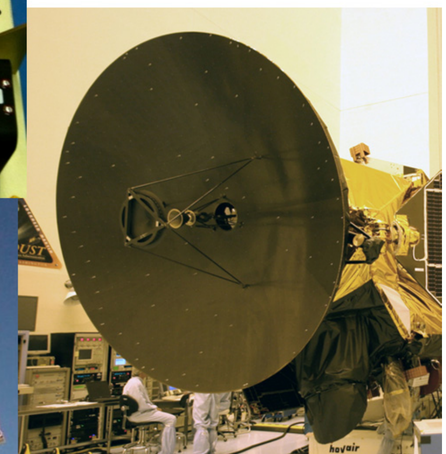
The power received by the 70m Deep Space Network (DSN) antenna from Voyager is so small that if it were to be accumulated for 10 trillion years it can power a refrigerator light bulb for one second!!!



Meeting the Challenges of Deep Space Communications

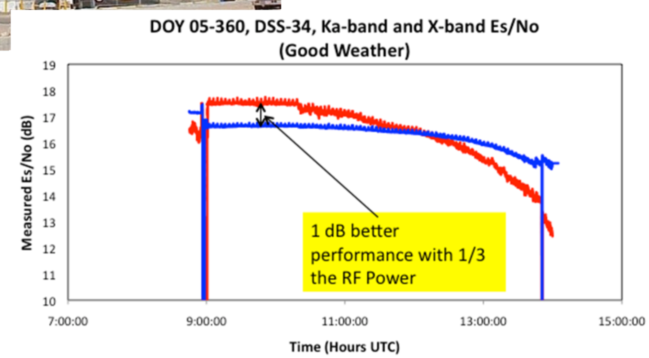
- P_T = TRANSMITTER POWER (RF)
- A_T & A_R = EFFECTIVE ANTENNA APERTURES
- f = FREQUENCY





$$\text{Data Rate} \propto \frac{P_T A_T A_R f^2}{T_S L_{TP} L_A L_{RP} R^2}$$

- T_S = SYSTEM NOISE TEMPERATURE
- L_{TP} & L_{RP} = ANT. POINTING LOSSES
- L_A = LOSS THROUGH ATMOSPHERE(S)
- R = RANGE BETWEEN S/C & DSS



Deep Space Communications Capability Drivers for Small Body Missions

- "Small Planetary Body" destinations may include:
  - Asteroids, Comets, Centaurs, Small moons (e.g. Mars, Jupiter), Icy Dwarf Planets, Trans-Neptunian Objects (TNO)
  - *Can range from close to Earth to the outer reaches of the Solar System*
  - Missions with high performance onboard instruments will require high data rates and high-performance, low-complexity data compression to handle huge data volumes
  - Examples: multi-spectral imagers and video cameras as well as radars & sounders to probe interiors & surfaces
  - *Missions with landed assets to perform in situ experiments will additionally require robust ad-hoc communication networks*
- Unusual dynamics of orbiting or landing on small planetary bodies may require special testbeds/tools to predict link performance
  - Meeting the often-driving navigation requirements levied on communications system assets can enable additional, opportunistic science (e.g. Radio Science)
- If astronauts eventually are sent to these destinations, even higher data rates may be required

Meeting the Challenges of Small Planetary Body Exploration

- **Planetary exploration is expensive, so the community of Small Planetary Body scientists needs to strategically leverage both ground and space assets**

- **This presentation will address:**
  - **Communications capabilities that will be needed for space missions for Small Planetary Body exploration**
  - **Utilization of large ground-based radar capabilities for Small Body remote sensing and mission planning**

- **NASA Program Executive will supply this slide**
  - **will include NASA thrust areas as they relate to SBAG + more**

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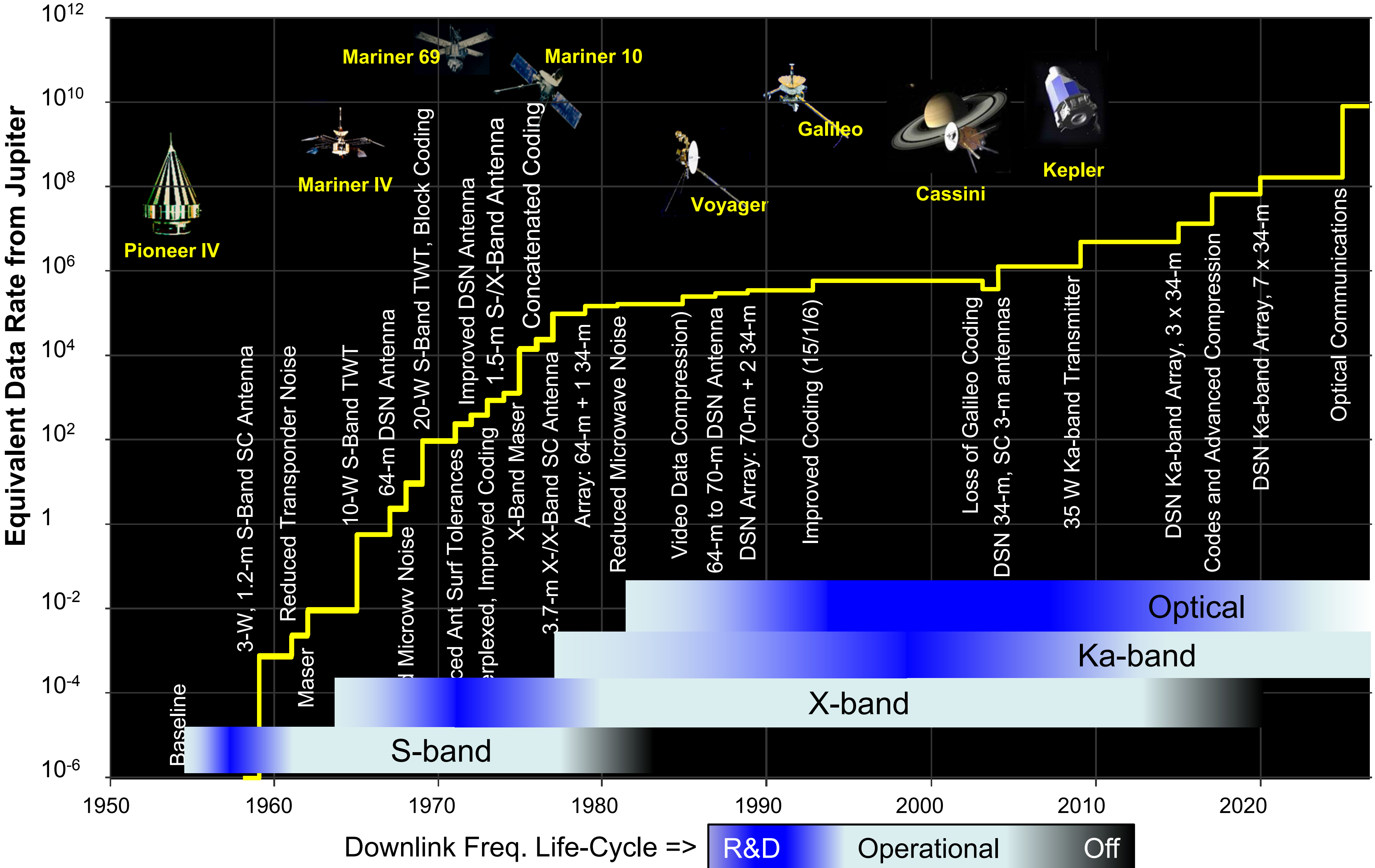
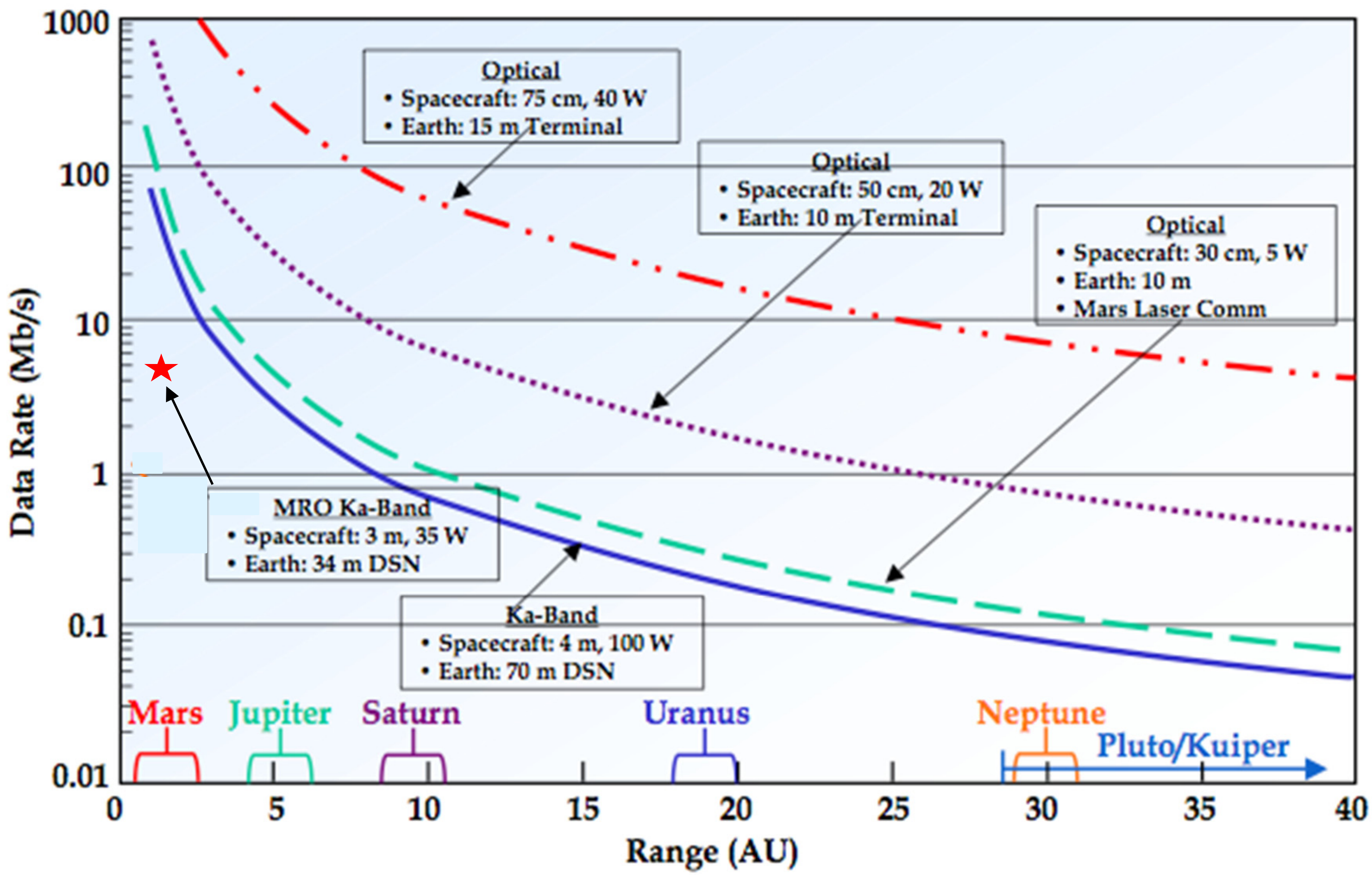
Deep Space Communications Downlink Data Rate Evolution



24-Jan-2011 SBAG Workshop

Challenges of Deep Space Communications for Small Body Exploration

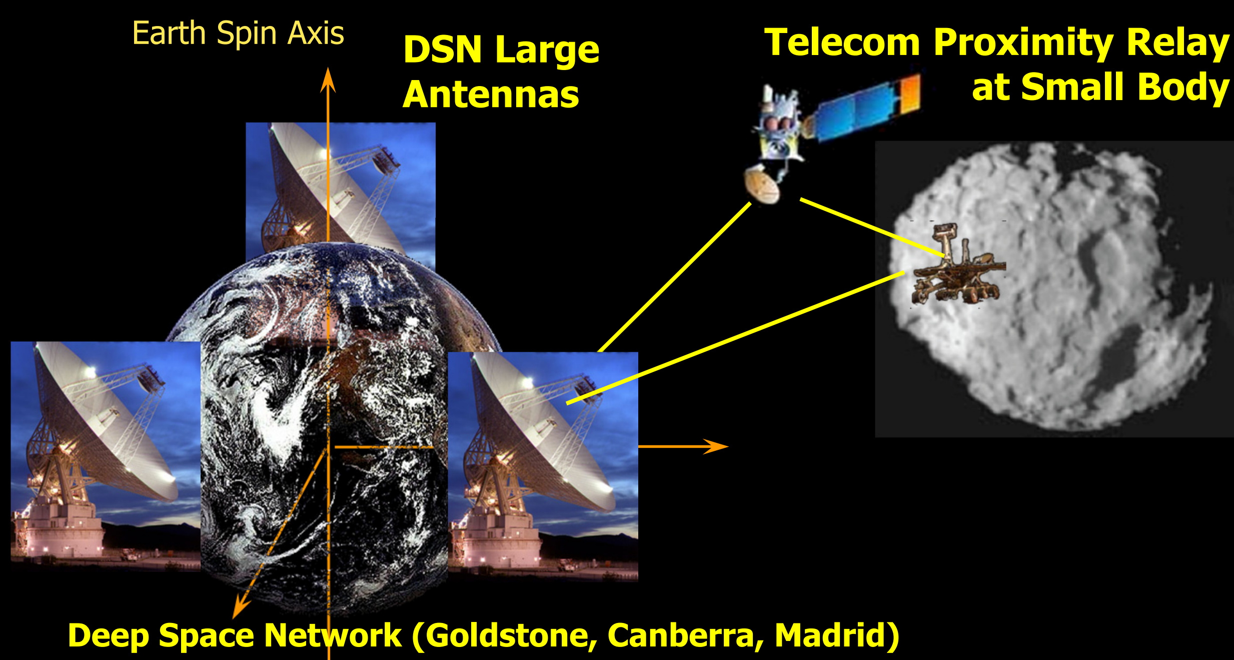
- **Small body missions would carry instruments (imagers and radars) that produce high data volumes. The challenge for telecom is magnified by the large distances. In addition to advances in RF telecom (e.g. higher power amplifiers, larger antennas) optical communications would likely be needed for the highest data rates.**



Communications Scenarios for Small Body Missions

- SBAG priorities include in situ analysis with landed elements and eventually sample return.
- Landed elements with tightly constrained power require a more capable orbiter as a science relay. This architecture can also support sample return.
- Next-generation flight communication systems can help by increasing data throughput, reducing S/C complexity and offering greater flexibility

DTE/DFE Data Rates		Proximity Data Rates	
Rx	Tx	Rx	Tx
Now			
~4 kbps	~10 Mbps	~2 Mbps	~2 Mbps
Next-Generation			
~40 Mbps	~150 Mbps	~40 Mbps	~40 Mbps



Challenges of Deep Space Communications for Small Body Exploration

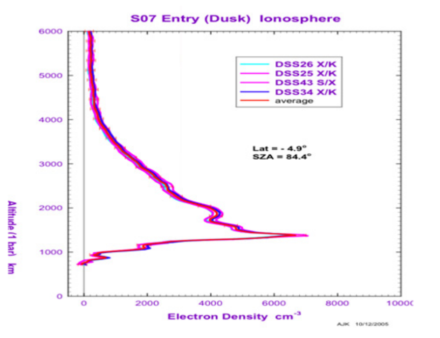
- **Present-day missions utilize one radio for proximity links (e.g. landed element communicating with an orbiter), and another radio for the long-distance direct-to-Earth link.**
- **Next-generation NASA deep space transponder under development will:**
  - **combine the proximity and long distance telecom functions into one device, reducing mass & power for missions which need both.**
  - **simplify the flight system by pushing functionality into the "radio".**
  - **meet NASA's architecture standard for Software Defined Radios, and support full reconfiguration and/or reprogramming before and *after* launch.**
  - **enable flight system to:**
    - **a) "react" to science learned and/or**
    - **b) "repurpose" S/C on an extended mission,**

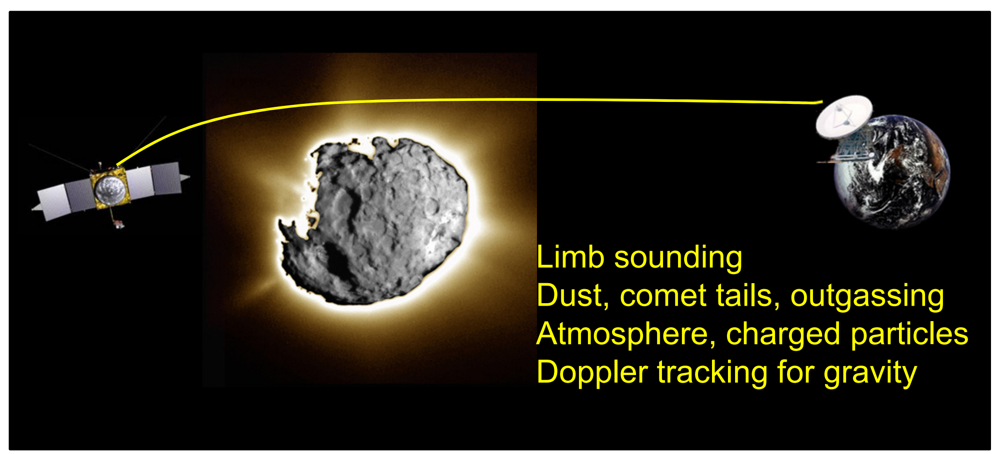
    allowing near-complete reconfiguration and/or reprogramming of the full comm system.

Radio Metric Tracking and Radio Science

- **Telecom can provide precision tracking for Navigation and for Radio Science**
  - **Radio Science: occultations probe planetary atmospheres, ionospheres, rings, surfaces, shapes.**
  - **Precise Doppler & Range, which are utilized for Navigational Tracking, enable the spacecraft to closely approach the target, and can determine planetary masses, gravitational fields, and surface/internal structure**
    - **Radio Science motivates development of the most sensitive tracking systems (10^{-15} Doppler [micron/sec level]).**
    - **Future missions (Juno, Europa Orbiter, Titan Lander, Small Body explorers) could emphasize Radio Science integrated with precise Tracking and with the Telecom subsystem**

Radio Science





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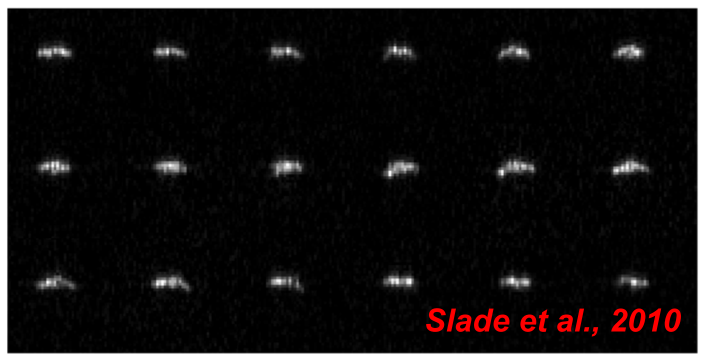
Small Body Exploration: Importance of Ground-Based Observatories

- **Ground-based remote sensing can (a) assess potential for NEOs to collide with Earth, and (b) catalogue and characterize small body destinations for future missions**
- **The two currently existing planetary radar facilities, Goldstone DSN 70-m and 34-m antennas, and Arecibo radio observatory, have complementary capabilities**
- **Arecibo has the highest sensitivity for distant object detection. However, Goldstone:**
  - **Achieves finer resolution (3.75 vs 7.5 meters)**
  - **Sees more of the sky (~80% vs ~30%) and views an object for a longer time**
  - **More easily tracks a very close object (by reception at a second antenna)**

First 3.75-m resolution radar images of an asteroid (2010 AL30) at Goldstone DSN site (asteroid size is only 30 m)



2010 NASA-requested NRC report on NEO threat to Earth states:

"Finding: The Arecibo and Goldstone radar systems play a unique role in the characterizations of NEOS, providing unmatched accuracy in orbit determination, and insight into size, shape, surface structure"

"Recommendation: …NASA and NSF should support a vigorous program of radar observations of NEOs at Arecibo ... and Goldstone for orbit determination and characterization of physical properties."

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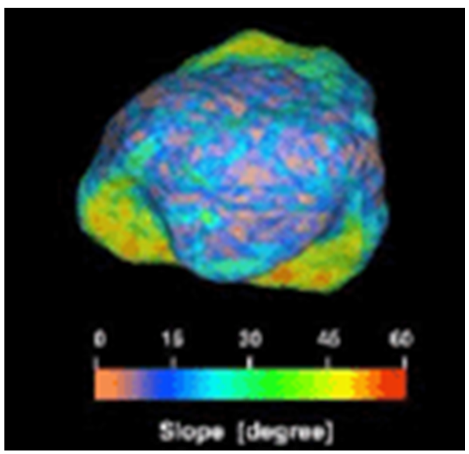
Role of Radar in NEO Observations

For more information on NEO radar see: http://echo.jpl.nasa.gov

- **Optical/IR observations are used to discover NEO population**
- **Once NEOs are found, radar observations can uniquely provide:**
  - **Much more precise (by 10X to 100X) ephemerides for newly discovered NEOs, key for assessing threats and planning missions**
    - **Computation of motion decades to centuries into the future**
  - **High resolution images (as fine as 3.75 meters), orders of magnitude better than optical**
  - **3-D shapes; sizes; spin states; and surface features**
  - **Discovery of binary and triple objects: estimate orbits, bulk masses and densities**

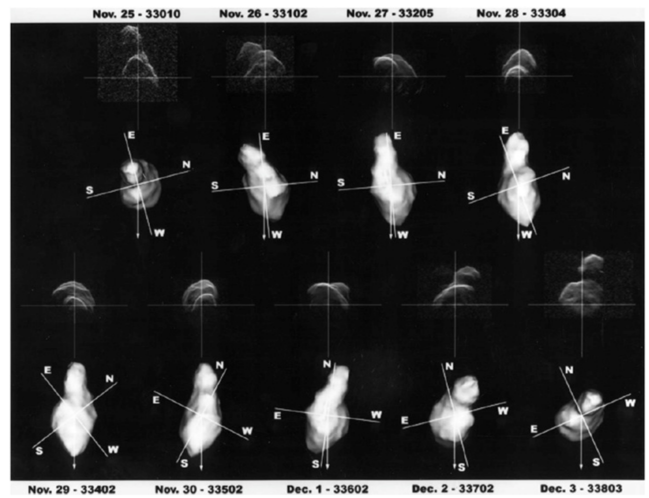


Goldstone radar observations of asteroids:

6489 Golevka (colors indicate gravity slopes)

Hudson et al., 2000

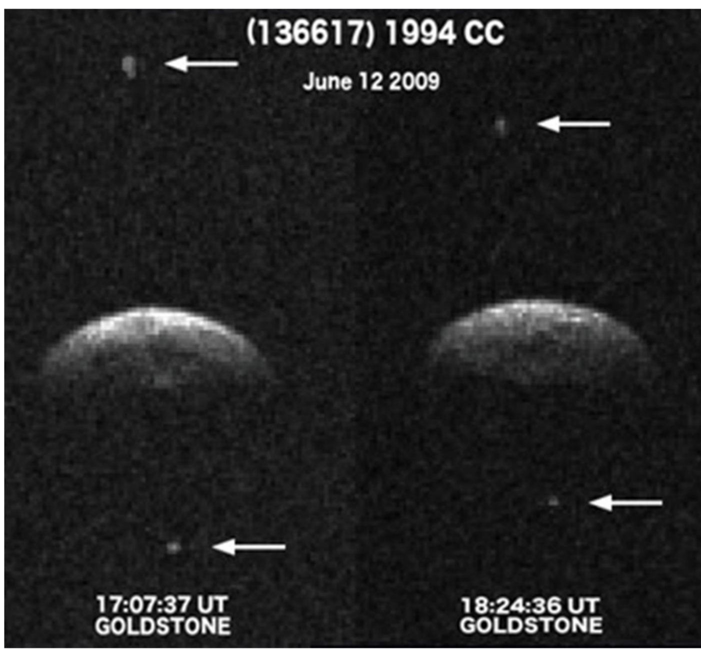
4179 Toutatis ~ 5-km in size; high resolution delay-Doppler images from radar compared to plane of sky appearance



Ostro et al., 1999

Too Few NEOs Are Being Observed with Radar

- **The two existing radar facilities (Goldstone and Arecibo) are primarily used for non-radar activities: currently only about 2% of the time is used for radar**
- **These ground radar facilities currently observe about only about 5% of NEOs they could observe with more observing time**
  - **In total, radar has observed 271 of 7674 known NEOs (as of 12/8/10)**
- **This situation will get much worse with the increasing discovery rate**
  - **Current DSN radar observation rate is up to 60X less than pace needed to keep up with potential optical discoveries**

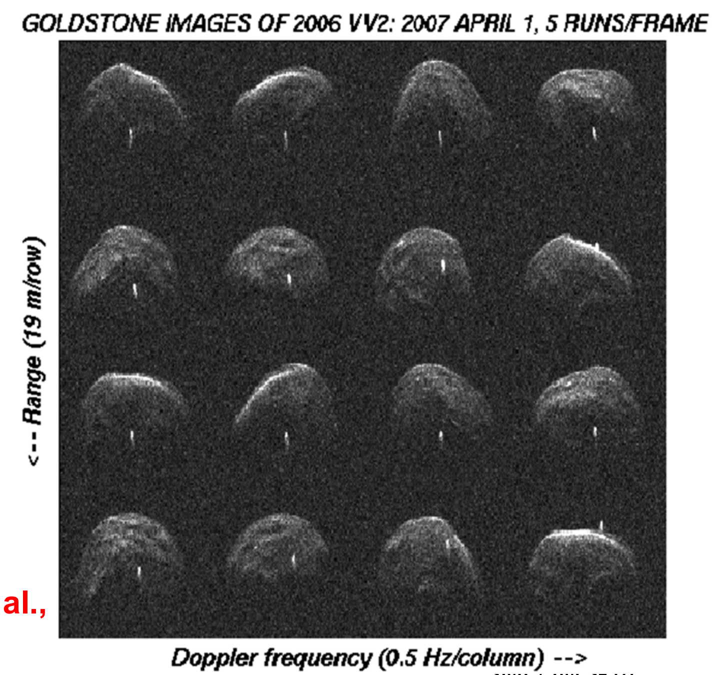


Goldstone radar images of trinary asteroid system

Goldstone radar images of binary asteroid system

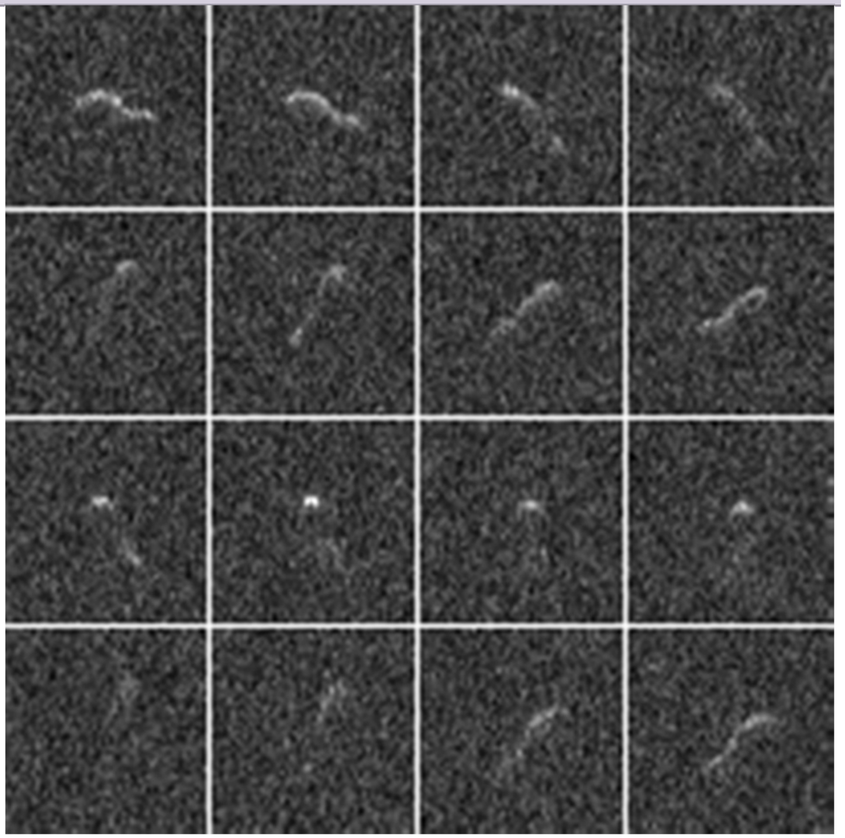
Brozovic et al., 2010

Benner et al., 2007



Example: Radar Aids Recent NEO Mission

October 2010: From 50 lunar distances away, returned important data prior to EPOXI spacecraft flyby of comet Hartley 2



John Harmon - Arecibo

National Astronomy and Ionospheric Center, Arecibo Observatory: J. Harmon, M. Nolan, E. Howell, J. Giorgini (2010)

Navigation & targeting:
- 70-km ephemeris correction
- Cut range uncertainty ~1 order of magnitude
- Revealed deficiency of non-gravitational acceleration model

Flyby science/imaging planning:
- Revealed shape/size (elongated contact binary)
- Rotation period
- Coma particle size, speed, direction

Radar has previously supported several asteroid missions

Clementine (1620 Geographos), NEAR (Mathilde), Rosetta (Lutetia), Dawn (Vesta and Ceres), Hayabusa (25143 Itokawa), Hayabusa (4660 Nereus – original target); featured in proposed New Frontiers and Discovery missions

Possible DSN Options for Increasing Radar Observation Rate

- **Increase observation rate at Goldstone**
  - **Radar observations must become less of an R&D operation and instrumentation needs to be more robust**
  - **Radar observations need improved priority on antenna**
- **Implement radar at one or two other DSN 70-m antennas**
  - **Achieves 2X-3X more radar observations than single 70m**
- **Build new 34-m DSN tracking station at Goldstone**
  - **Could free up large fraction of 70-m time for radar observations**
- **Build a new dedicated DSN radar facility**
  - **Might best meet NASA’s needs for radar observation volume**

Challenges of Small Body Exploration

- **Telecom**
  - **Moving to Ka-band (higher frequency)**
  - **Larger space antennas; arrays of ground antennas; improved pointing**
  - **Higher power flight transmitters**
  - **Next generation flight transponders**
  - **Precision Radio Science integrated into Telecom**
  - **Optical Communications**

- **Ground-based radar observations**
  - **NASA/JPL Goldstone planetary radar; Arecibo Observatory**
  - **Cataloging and characterization of populations of comets, NEOs, and other Small Planetary Bodies**
  - **Surveys of Small Bodies using ground-based radar facilities will inform for selection of priority destinations for space missions**
  - **Options exist to enhance and improve ground radar capabilities**

Citations / References

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